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Source: Journal of Coastal Research, 75(sp1) : 1187-1191

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI75-238.1

Journal of Coastal Research	SI	75	1187 - 1191	Coconut Creek, Florida	2016

Evaluation of Runup Characteristics on the NSW Coast

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ABSTRACT

Morris, B.D., Foulsham, E., Laine, R., Wiecek, D. and Hanslow, D., 2016. Evaluation of run-up characteristics on the NSW coast. *In:* Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds.), *Proceedings of the 14th International Coastal Symposium* (Sydney, Australia). *Journal of Coastal Research*, Special Issue, No. 75, pp. 1187 - 1191. Coconut Creek (Florida), ISSN 0749-0208.

Communities and infrastructure along the coast of New South Wales, Australia, are vulnerable to coastal inundation from the combined impacts of ocean tides, storm surge, wave setup, wave run-up and wave overtopping. The focus of the current work is to examine the potential for coastal inundation on beaches and dunes on the open coast of NSW through the evaluation of wave run-up. To achieve this we combine information on tides, surge and wave run-up to examine dune overtopping potential. The study utilises data from the NSW wave and ocean tide gauge network and an extensive set of beach profile and grainsize data covering over 200 beaches as well as available photogrammetry and LiDAR data. Ocean still water level and design nearshore wave conditions are used together with beach slope data to calculate wave run-up height. Choice of appropriate wave run-up formulation is evaluated through the use of available long term datasets from Narrabeen and Moruya. Geographical variability in relevant beach/dune characteristics including beach slope and dune height are examined using survey (RTK-GPS), photogrammetry and LiDAR data. Overtopping potential for various design events (e.g. 5y, 20y, 100y storms) is examined through the overlay of predicted run-up heights on high resolution digital elevation models at each pilot study site.

ADDITIONAL INDEX WORDS: .*Inundation, Exposure, Coastal hazards, Coastal risk.*

INTRODUCTION

The New South Wales (NSW) coastline stretches for over 1590 km and has over 750 sandy beaches (Short, 2007). Over 85% of the population live within 50 kilometres of the coast (ABS, 2004) which is known to be highly vulnerable to both erosion and inundation (DCC, 2009; Cechet *et al.*, 2012).

Recent investigations into the extent of the risk posed by coastal hazards along the NSW coast has shown that on the open coast around 2100 properties are exposed to coastal erosion at present. With sea level rise, coastal recession is projected to increase the exposure of coastal properties to erosion. By 2050 total properties at risk is projected to increase to around 1900 primary and an additional 1900 secondary addresses and by 2100 to around 3200 primary and an additional 3700 secondary addresses (OEH, 2015).

On the open coast in NSW, waves are the dominant contributor to inundation. Wave runup is known to reach levels many meters above ocean tide still water level (NSW Government, 1990). The broad scale risk assessments undertaken to date (DCC, 2009; Cechet *et al.*, 2012) have not taken this into consideration, thus the extent of the problem here is largely unknown.

DOI: 10.2112/SI75-238.1 received 15 October, 2015; accepted in revision 15 January, 2016.
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Wave runup in this study is defined as the landward extent of wave uprush measured vertically from the still water level. The runup includes the combined effects of wave setup (super-elevation of the mean water surface) and individual wave uprush. The still water level is the average water surface elevation at any instant including the effects of tides, storm surges and other contributors to regional ocean levels but excluding effects from waves.

In the current study we examine contributors to both still water levels and wave runup along the NSW coast and develop a pilot method for a first pass assessment of open coast inundation hazard.

Regional Setting

The NSW coast is aligned to the predominant south east swell and experiences a moderate to high energy wave regime. The shoreline is comprised of areas of rocky cliffs and headlands joined by sandy beaches. On the coast south of Sydney, the beaches are predominantly pocket beaches isolated by rocky headlands, whilst in the north of the state the beaches tend to be longer and alongshore rates of sand movement are higher, predominantly from south to north. NSW beaches also vary in type according to exposure to the modal SE-S wave direction and sediment grain size. Along shore variation in wave exposure also results in variation in characteristics within beaches with southern ends tending to be more sheltered than the exposed northern ends. Beaches in NSW are typically backed by high dunes which provide some natural defence against storm surge and wave inundation. Dune height characteristically varies along shore with higher dunes to the northern ends associated with increased exposure to wave and wind.

Coastal water levels are influenced by a variety of astronomical, meteorological and oceanographic factors. These include both tidal and non-tidal contributors to regional still water levels as well as the effects of waves including wave setup and wave runup. Tides along the NSW coastline are semi-diurnal in nature and have a pronounced diurnal inequality. The mean spring range is 1.2 m while the mean neap range is 0.8 m (MHL, 2012). Tidal range varies slightly along the coast with an increase of around 0.2 m from south to north (MHL, 2011).

Variations in water level due to non-astronomic factors are common along the NSW coast and MHL (1992) shows that anomalies of 0.3 m occur at return intervals of months, and thus become a significant addition to tidal predictions. Drivers of tidal anomalies include variations in air pressure and wind stress which during storms is known as 'storm surge'; coastal trapped waves; ocean currents; steric effects; seiches; tsunamis; Rossby waves etc. These processes operate over a wide range of time frames.

The NSW coast is subject to a moderate to high energy wave climate predominantly from the south to south-east (Harley *et al.*, 2010). The average offshore significant wave height is ~1.5 m and average peak period is ~9.5 s (Lord and Kulmar, 2000). The wave climate is periodically affected by large wave events originating from coastal storm systems which vary both spatially and temporally in their genesis, intensity and track. Very large storm events also occasionally impact the coastline (Shand *et al.*, 2011).

At a regional scale the occurrence of and exposure to different storm types varies with latitude along the NSW coast (Shand *et al.*, 2011). The relatively steep and narrow nature of the continental shelf ensures that loss of wave power to bed friction is minimal across the shelf (Wright, 1976) although the presence of headlands and offshore reefs does lead to significant alongshore variation in wave climate.

METHODS

Available runup formulations are reviewed and evaluated against field runup observation data collected from a variety of sites along the NSW coast. To enable broader state-wide application a new relationship between beach slope and grainsize is developed. Nearshore wave transform relationships are used to address along shore variation in exposure to extreme storm waves and to predict runup height for a range of storm wave conditions.

Predicted runup is compared to dune crest elevation for pilot sites to provide a first pass indication of dune overtopping potential and open coast inundation hazard. The pilot sites are chosen to be representative of a diverse range of beach types, Figure 1. These include Kingscliff, Mooball/New Brighton, Brunswick Heads, Belongil, Main Beach/Clarks, Terrigal/Wamberal, Avoca, Narrabeen/Collaroy, Moruya Beach, and Pedro Beach.

Figure 1. Map of New South Wales, Australia, showing location of pilot study sites.

The beach slope in the swash zone can be expressed as a function of the grain size, thus as part of the current project an extensive beach survey data set was collected from some 200 beaches along the NSW coast in 2013. These survey data include beach profiles using RTK-DGPS and sediment sampling. This data set (OEH) allowed the determination of the beach slope and grain size in the swash zone. A second, more comprehensive, set of grain size data (Short, 2007) which encompasses almost all of the 720 beaches in NSW was also obtained from Prof. Andrew Short (USyd).

These two data sets were collated taking into consideration the method of grain size analysis. It is well documented that the laser diffraction method generally measures larger particle sizes than when compared to results from sieve analyses (Baldock and Felder, 2013). The Short (2007) dataset, which was analysed using the sieving method, was converted to reflect a laser diffraction analysis following Rodríguez and Uriarte, (2009).

Using the measured swash slope and corresponding swash sediment grain size from the OEH survey data a linear fit was performed and was used to calculate swash beach slope for sites where only information on grain size was available. Settling velocity was also calculated using the grain size data following the methods of Hallermeier (1981).

In order to evaluate runup both offshore and nearshore wave parameters are required. In this study offshore wave height (H_0) and period (T_{p0}) for a set of three Annual Return Intervals (ARI), 5y, 20y and 100y, are used (Shand *et al.*, 2010). These offshore ARI wave data are directionally partitioned into north-east (0 - 90), east (90 – 135) and south-east (135 – 180). This allows for consideration of directionality in storm wave climate and in particular the lower probability of storm waves from the north.

To obtain a scaled nearshore wave height (H_S) the NSW Nearshore Wave Transfer Tool (Baird and MHL, 2015) was used. This tool transforms wave parameters from deep water (***i.e.*** nearest wave buoy location) to the 10m depth contour. Transforms are performed on each of the three directionally partitioned offshore wave heights to obtain directionally partitioned scaled nearshore wave heights which are then combined using directional likelihood tables to obtain a single H_S value.

Each of the pilot study sites were partitioned into three spatially equal sectors, nominally North, Central and South in order to reflect the potential differences in wave exposure within a beach embayment. A distinct H_S estimate was obtained for each of these sectors using the above technique.

Runup formulae have been recently reviewed for the NSW coast by Shand *et al.* 2011 and Power *et al.* 2013. In the current study the following formulae are used initially; Hunt (1959), Mase (1989), Nielsen and Hanslow (1991), Holman (1986), Hanslow and Nielsen (1995) and Stockdon *et al*. (2006). A seventh formula, Hunt (1959) scaled, was also included where H_0 was replaced with H_S in the original formula.

In order to determine the most appropriate formula, or set of formulae, to use in estimating maximum runup (Rmax) along the NSW coast a comparison was made between formula results and field data. Long term topographic survey data were obtained from Prof. Andrew Short for three beaches; Narrabeen/Collaroy, Moruya Beach and Pedro Beach (Figure 1). These survey data consist of nominally monthly surveys of several fixed profiles per beach. More details of these survey data are outlined in Short *et al.* (2014).

In addition to topographic beach profile data, these data sets also contain an estimate of maximum runup elevation at each profile location. These elevations were compared to runup values determined using the seven runup formulae. To obtain estimates of runup values for each of the three sites the grain size from the Short (2007) data set was used to calculate the swash beach slope. Offshore wave data for the day preceding each survey was filtered to obtain the maximum wave and water level conditions and these wave parameters were transformed to obtain the nearshore wave heights at each profile location. Using these data and the runup formulae a set of maximum runup estimates was obtained at each profile for each survey at the three sites.

The maximum of these runup estimates over the whole survey period at each of the three sites were then compared to the corresponding maximum measured runup values. The accuracy of the calculated maximum runup estimates as compared to measured values were then used to rank the seven formulae. The results from all three sites ranked the methods of Hunt (1959) scaled, Hanslow and Nielsen (1995) and Holman (1986) as the three 'best' methods and thus they were selected for use in the risk assessment.

In order to compare the calculated maximum runup elevation with the morphology of each study site, the location of the dune crest was manually digitised using hill-shaded topography DEM (created from best available LiDAR data) in association with the best available ADS40 aerial imagery. Elevations, relative to AHD, were extracted at each vertex in the dune crest linear feature, as well as at 10 m intervals along the feature.

The Still Water Level (SWL) was added to the calculated maximum runup (Rmax) values in order to compare with these dune crest elevations. For each study site the HHWSS values (MHL, 2012) from the nearest ocean tide gauging station were used as a basis for SWL. To account for non-astronomical water level variations the extreme water level values for each ARI scenario were added to the appropriate HHWSS water level to obtain the SWL. The values used in this study are 0.43, 0.47 and 0.51 m for the 5y, 20y and 100y ARI respectively (SMEC and UQ, 2013).

The elevation of the dune crest (E_D) for each study site was then compared with the elevation of the maximum runup (E_R = Rmax + SWL) to evaluate the inundation potential. The Rmax used in this comparison is the mean of the results for the top three ranked formulae along with the corresponding standard deviation (σR). Runup inundation potential is defined as High, Medium or Low as shown in Table 1. Since each of the pilot study sites were partitioned into North, Central and South sectors to reflect the potential differences in wave exposure a distinct Rmax value, and thus E_R, was calculated for each sector.

Table 1. *Definition of conditions used for assessment of runup inundation potential.*

Runup inundation potential	Condition
High	$E_D < E_R - \sigma R/2$
Medium	$E_R - \sigma R/2 < E_D < E_R + \sigma R/2$
Low	$E_D > E_R + \sigma R/2$

RESULTS

An example of the evaluation of runup inundation potential is shown in Figure 2 using 5y ARI runup values for the Avoca site.

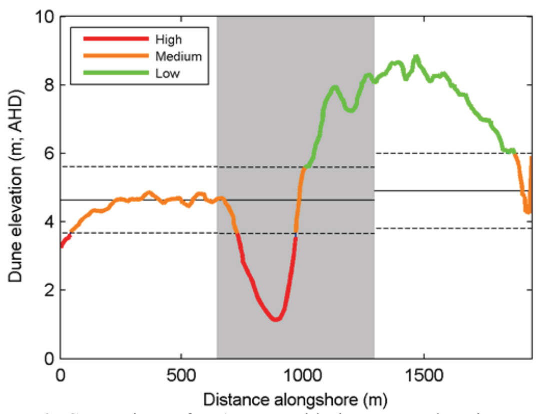

Figure 2. Comparison of 5yARI E_R with dune crest elevation at Avoca. Distance alongshore is measured south to north with the Central sector shaded. Estimated runup elevations and standard deviations are shown for each sector as solid and dashed lines respectively. Coloured lines indicate runup inundation potential.

In this figure the runup inundation potential is colour coded such that red, orange and green indicate high, medium and low respectively. The shading in the figure is to distinguish the three sectors, *i.e.* the Central sector is shaded, and the estimated runup elevations and standard deviations are shown as solid and dashed black lines respectively. The runup inundation potential can also be expressed quantitatively as a percentage of length of the beach or shown graphically as in Figure 3.

Figure 3. Map showing Avoca site with level of runup inundation potential shown for the 5y ARI case.

Examining the case of the Avoca site and using the 5y ARI values it can be seen (Figure 2) that the South sector dune field is between 3-5 m elevation and E_R is ~4.6 m resulting in the sector generally being classified as having Medium runup inundation potential. The exception in this sector is the far southern corner of the beach where runup inundation potential is high. Here a carpark has replaced the dune field. The Central sector includes the entrance to Avoca Lake with very low elevation and thus classified as High potential, however the remainder of the sector consists of a high ($E_D > 6$ m) dune field classified as Low potential since E_R in this sector is ~ 4.6 m. Likewise in the North sector the high dune field ($E_D > 6$ m) results in a Low potential classification generally despite E_R being larger (~4.9 m) in this sector, with the exception of a Medium potential area ($E_D < 5$ m) in the far north.

The evaluation of runup inundation potential was undertaken for all ten pilot study sites for the three ARI cases and a summary of the results, as a percentage of length of the beach, are shown in Table 2. The Medium and High potentials have been combined to obtain a conservative estimate of the inundation potential.

Table 2. *Runup inundation potential as percentage of length of beach for three ARI cases.*

Study Site	5y	20y	100y
Kingscliff	6	8	9
Mooball/New Brighton	8	10	13
Brunswick Heads	0	0	0
Belongil	7	7	7
Main Beach/Clarks	0	0	0
Terrigal/Wamberal	59	73	76
Avoca	56	63	69
Narrabeen/Collaroy	48	57	85
Moruya Beach	19	22	26
Pedro Beach	13	14	15

DISCUSSION

The findings from the evaluation of runup inundation potential at the ten pilot sites show similar trends despite the variations of conditions at each site, *i.e.* wave exposure, grain size, swash slope etc. Generally, there is less runup inundation potential at southern ends due to reduced exposure to predominant SE wave climate. This is highlighted in the extreme case of the Main Beach/Clarks site where there is almost no exposure to SE waves and hence no inundation potential even in the largest (100y) wave case (Table 2). At the central to northern end of the beach embayments the inundation potential is also decreased, in this case by the presence of higher elevation dune fields, even though the runup maximum values are greater due to greater wave exposure. In some cases (*i.e.* Avoca) the dune elevation is twice that of the runup elevations.

Runup formulations are generally sensitive to variations in both swash slope and wave height in particular since these are the primary drivers. Limitations of the method presented here thus include uncertainties in the swash slope which is highly spatially and temporally variable. Grain size is used in this study to calculate swash slope which decreases the variability and also allows assessment at sites where no survey data are available. Uncertainties in the wave heights are also a limitation of the method, however these have been mitigated by use of a nearshore wave transfer tool to obtain H_S. This is particularly important when considering that the three best ranked formulae used for the assessment are dependent on H_S.

CONCLUSIONS

The assessment of pilot sites using the method presented here shows sheltering from predominant SE wave climate decreases runup inundation potential at southern ends of beach embayments whilst higher elevation of dune fields at northern ends generally also decreases inundation potential despite higher wave and runup exposure.

The methodology used in this pilot study will be applied to beaches state wide in NSW to obtain a first pass assessment of runup inundation potential. Future work will also include the examination of storm runup and also an assessment of runup inundation under sea level rise which would affect the coastal water levels.

ACKNOWLEDGMENTS

Funding for this study was provided by the NSW Government Natural Disasters Resilience Program. Water level data was kindly provided by Manly Hydraulics Laboratory. Terrain data was provided by NSW Land and Property Information. Grain size, beach profile and swash observations were provided by Prof Andrew Short (University of Sydney).

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